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MAGNET DESIGNS FOR THE ERHIC RAPID CYCLING SYNCHROTRON*

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Abstract

Presently the electron-ion collider eRHIC is under design, which aims to provide a facility with a peak luminosity of $10^{34}\text{cm}^{-2}\text{sec}^{-1}$. Part of the eRHIC design is a rapid cycling synchrotron, which accelerates electrons from 1–18 GeV.

In this paper we present conceptual designs of the required dipole, quadrupole and sextupole magnets. The magnets meet the specifications in terms of performance and field quality with an acceptable power dissipation. The power supply requirements are also discussed.

INTRODUCTION

One of the options for an injector for the eRHIC accelerator is a Rapid Cycling Synchrotron (RCS), which accelerates electrons from 1–18 GeV. For this paper we assume a ramp rate (linear rise to full field) of 200 ms and a duty cycle of 1 Hz. The RCS and the lattice is described in more detail in [1].

This paper deals with a description of the dipole, quadrupole and sextupole magnets required for this injector.

SIMULATION DETAILS

All magnets are assumed to be made of 3% SiFe laminations which are 0.014 in thick. To estimate the core losses we use data from [2]. It was found that the core losses generally due to the low duty factor are not a concern and contribute less than 1% to the overall power dissipation of the magnets.

To calculate eddy currents and magnetic fields we use the commercial finite element code COMSOL Multiphysics [3]. Eddy current effects in the yoke were found to be minimal.

DIPOLE MAGNETS

The main requirements for the RCS dipole magnets are summarized in Table 1; as shown in the table, in total 384 magnets are required with a length of 4.24 m. The dipole field at peak energy is 0.234 T; the relatively low dipole field helps to keep the power dissipation in the excitation coil and the core losses low.

The field quality should be better than 1×10^{-3} in an aperture of 30 mm; the physical gap of the dipole magnets is 40 mm to allow for sufficient space for a beam pipe.

Figure 1 shows the geometry of the dipole magnet. As shown in the figure, a simple H-frame geometry is chosen for this magnet. The excitation coils are simple racetrack coils with two turns each.

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Table 1: Specifiaction RCS Dipole Magnets

Parameter	Value	Unit
Magnetic length	4.24	m
Dipole field, min	0.012	T
Dipole field, max	0.234	T
Good field, radius	15	mm
Weight iron	401	kg/m
Gap height	40	mm
Cross-section conductor	4 turns 40x40	mm^2
Current density peak (avg.)	1.3	A/mm^2
Ampere turns per coil	4000	A
Power loss per len. magnet	50	W/m
Magnetic energy	150	J/m
Inductance	0.75	μH/m
Voltage	0.375	V/m

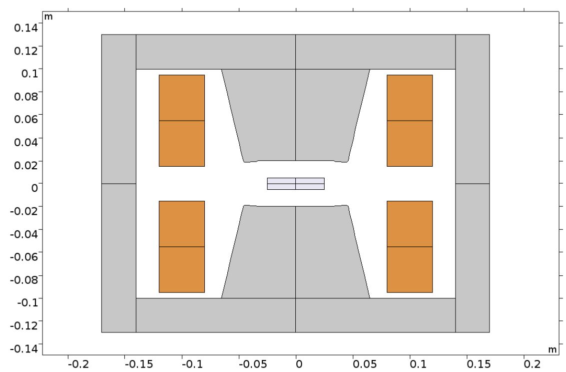

Figure 1: eRHIC RCS dipole magnet.

The peak magnetization is kept relatively low at 0.7 T to minimize the core loss in this region. Assuming a pessimistic 50 Hz pulse the average core losses are expected to be 2.41 W/m for a single cycle. In reality the core losses should be much less, as the power dissipation is roughly proportional to the frequency.

Figure 2 shows the field quality at peak field on the centre plane; it was verified that the field quality does not change significantly during the ramp.

Eddy currents in the excitation coil do not play a significant role at this frequency, which is shown in Fig. 3. The figure shows the current density in horizontal direction for different times during the ramp; as shown, the current density varies, but this does neither affect the field quality nor the power dissipation (the power dissipation is almost identical in comparison to pure I^2R losses).

Figure 4 shows the coil current and voltage (per meter length of magnet) evaluated by finite element analysis for a 200 ms rise time. As shown in the figure, the voltage drop

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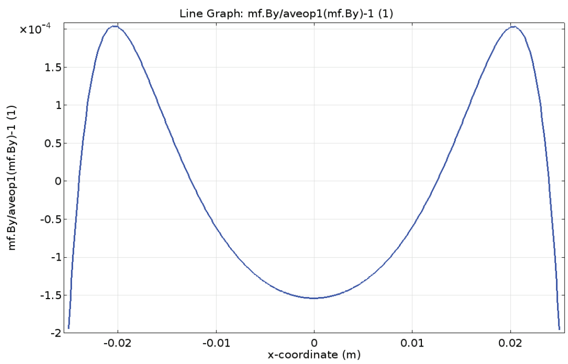

Figure 2: Field quality $\Delta B/B_0$.

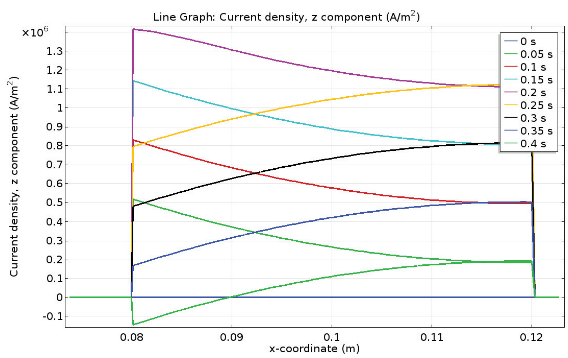

Figure 3: Current density in the excitation coil during the ramp.

is mostly inductive. Voltage and coil current can be tuned by changing the number of turns to suit power supply needs if necessary.

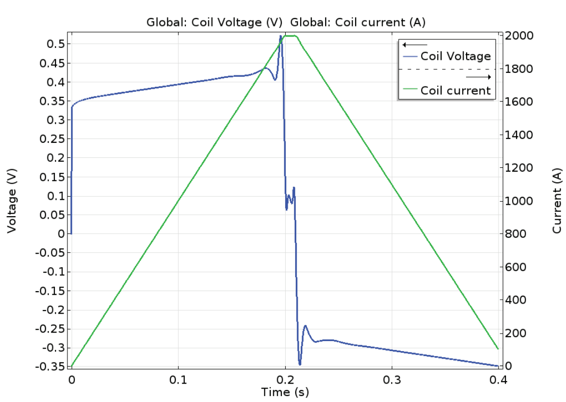

Figure 4: Coil current and voltage (per meter length) of the RCS dipole magnet.

QUADRUPOLE MAGNETS

The main parameters for the RCS quadrupole magnet design are shown in Table 2; in total 534 quadrupoles are necessary for the entire RCS ring (half focusing and half defocusing quadrupoles). Each quadrupole is 0.6 m long; the required peak gradient is 22.2 T/m. The required field quality is 1×10^{-3} in an aperture of 30 mm. The preliminary geometry is shown in Fig. 5.

Table 2: Specification of the RCS Quadrupole Magnets

Parameter	Value	Unit
Qf/Qd magnetic length	0.6	m
Qf/Qd gradient	22.2	T/m
Qf/Qd physical width	0.6	m
Qf/Qd physical height	0.6	m
Weight iron	350	kg/m
Pole inscribed radius	18	mm
Cross-section	4 turns 20x20	mm^2
Current density peak (avg.)	2.5	A/mm^2
Ampere turns per coil	4256	A
Peak current	1064	A
Power Loss per len. magnet	220	W/m
Inductance	0.000768	H
DC Resistance	0.0008276	Ω
Magnetic energy	725	J/m

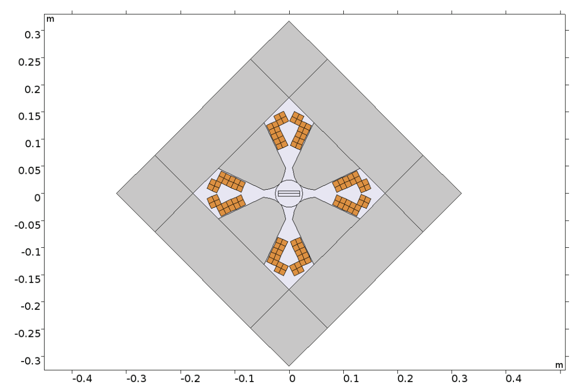

Figure 5: Geometry of the RCS quadrupole magnet.

The pole has the usual hyperbolic shape; the corners of the pole are adjusted to obtain a better field quality. The pole is moderately tapered which lowers the magnetization in this area. The peak gradient is shown in Fig. 6. The figures show that the peak gradient can be accomplished with good field quality while maintaining a magnetization of < 1.3 T in the pole.

Initial discussions show that coils with four turns for each pole lead to acceptable currents and voltages. Figure 7 shows the expected current and voltage (for a 1 m long magnet) for a 200 ms linear ramp. As shown in the figure, most of the voltage is inductive; the peak voltage per magnet is about 5 V per coil.

SEXTUPOLE MAGNETS

In total 420 sextupole magnets are needed, each 0.5 m long. The required sextupole strength is 280 T/m (dB_y/dx^2); the requested field quality is 1×10^{-3} in an aperture of 30 mm. The inscribed pole radius of the design, shown in Fig. 8, is 30 mm.

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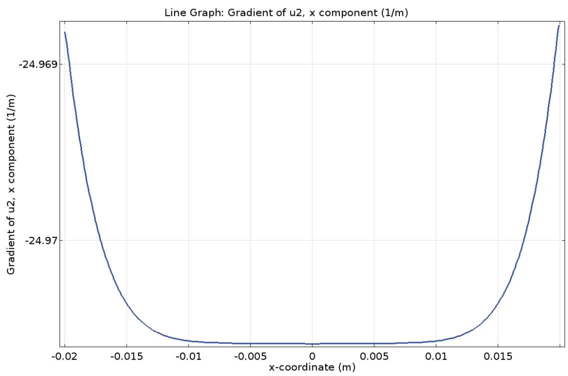

Figure 6: Simulated gradient of the RCS quadrupole magnet on the centre plane.

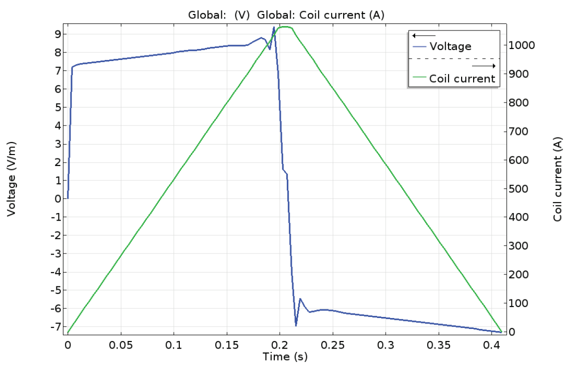

Figure 7: Coil current and voltage (per meter length) of the RCS quadrupole magnet.

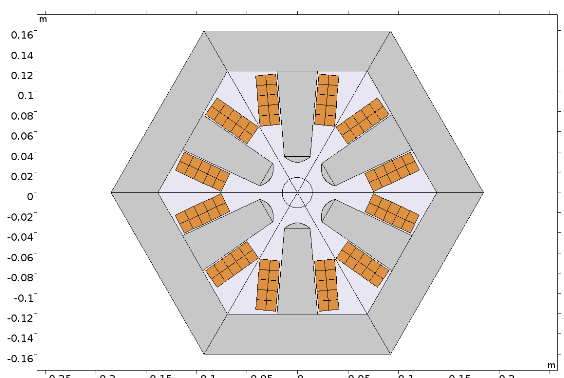

Figure 8: RCS sextupole magnet.

The pole shape is hyperbolic; the pole corners are adjusted to achieve the required field quality. The poles are slightly tapered which helps to reduce the magnetization. The poles are relatively slim in order to minimize flux leakage. The peak magnetization is calculated to be less than 1 T, which is conservative for 3% SiFe.

Preliminary calculations showed that 10 turns per coil will lead to reasonable currents and voltages for the power supply. Figure 9 shows the calculated coil current and voltage (per meter length of magnet) for the envisaged linear ramp of 200 ms. As shown in the figure, most of the voltage drop is inductive, even though there is also a significant resistive part. The peak excitation current is 700 A.

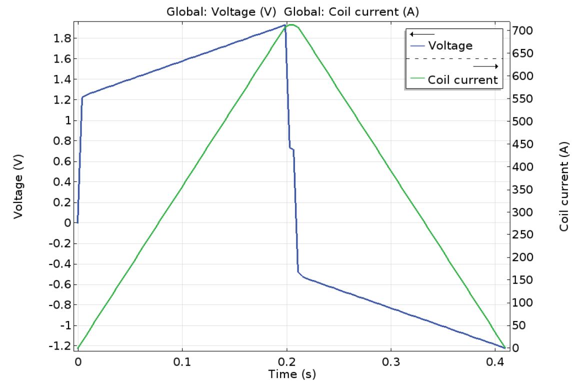

Figure 9: RCS sextupole magnet.

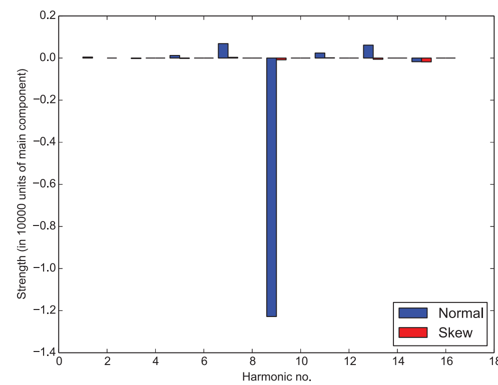

Figure 10: Higher order harmonics RCS sextupole magnet.

The field quality is evaluated in a 2D static simulation at peak excitation; Figure 10 shows the higher order harmonics. As shown in the figure, the higher order harmonics are well behaved. About 1.2 units of 18-pole is expected, which meets the field quality requirement.

CONCLUSION

This paper outlines magnet solutions for the eRHIC RCS injector. All magnet designs show an acceptable performance; core and eddy current losses at the envisaged ramp rates are not a concern. Studies show that this is even true for ramp rates of 100 ms, which could be required. In future studies 3D models will be developed.

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